HARVARD UNIVERSITY

HARVARD COLLEGE OBSERVATORY

SEMIANNUAL STATUS REPORT NO. 5

1 February 1965 to 31 July 1965

NASA Grant NsG-438

THEORETICAL AND EXPERIMENTAL STUDIES IN ULTRA-VIOLET SOLAR PHYSICS INCLUDING CONSTRUCTION OF LABORATORY PROTOTYPE FLIGHT EXPERIMENTS

Principal Investigator: Leo Goldberg

August 10, 1965

A. INTRODUCTION

We have continued our studies of solar physics both by experimentation in the shock tube spectroscopy laboratory and with theoretical methods. As in the past, main attention has been given to the important parameters: oscillator strength, absorption coefficient, cross section and life time.

In the laboratory the determination of such quantities is made by intensity measurements through photographic photometry. These last six months, however, have seen the introduction of new possible techniques with interferometry. In one case a Mach-Zehnder interferometer will lead through means of the hook technique to f-values, and in another the scanning Fabry-Perot provides the means of studying line profiles with high resolution.

The activities in molecular spectroscopy of the vacuum ultraviolet have increased considerably in the past six months. This was the result of the identification, early this year, from our shock tube spectra that the CO Fourth Positive System plays a dominant role in the solar spectrum.

In the following report, our progress in basic research is described in detail under Instrumentation, Atomic and Molecular Spectroscopy.

B. INSTRUMENTATION

We have recently completed a fourth shock tube for the spectroscopy laboratory. This tube was constructed from aluminum and its design is based on that of our stainless steel shock tubes. The fourth tube will be the light source for high resolution studies of line profiles with a scanning Fabry-Perot interferometer. We were able to acquire this special interferometer through the cooperation of Imperial and Holloway Colleges of the University of London with the encouragement of Drs. W.R.S. Garton and D. Bradley of these institutions. The interferometer plates were coated in Dr. Bradley's laboratory at Holloway College and then mounted on the barium titanate transducers. With this instrument we will be able to scan a line of half width of 0.05 Å with a finesse of 20 in 5 microseconds. The Fabry-Perot interferometer is presently being aligned and adjusted. The electronic equipment for scanning the Fabry-Perot plates and detection system are being built. A post-doctoral research physicist, Dr. Richard Day, of Dr. H. Griem's laboratory at the University of Maryland, has undertaken some of the initial adjustments of the Fabry-Perot.

The Littrow-type spectrograph has been completely constructed and is undergoing optical alignment and focus tests. Hartmann tests on the lens and grating assembly have indicated some small isolated regions of aberration. Further work using the Ronchi test is required to determine how the aberrations may be masked or corrected.

All optical and mechanical parts of the Mach-Zehnder interferometer have been manufactured and assembly and adjustment have begun. The test section of the shock tube, which must also be an optical member of the interferometer, has been designed. We anticipated that the integration of the Littrow spectrograph, Mach-Zehnder interferometer and shock tube test section will be completed by early fall.

A second gas handling system has been designed, assembled and put into operation. This second system has a number of advantages over the first, and retains the basic mixing and vacuum techniques along with the requirement that the gas mixtures contact only glass, stainless steel or teflon. Both gas handling systems are mobile and can be used with all the shock tube assemblies.

The computer programs to permit rapid and accurate reduction of photographic spectra are working smoothly with the output from our digitized microphotometer. As the result of these programs and our own requirements of higher accuracy both in wavelength and intensity, we have been acutely aware of the inadequacies of our existing microphotometer in the past six months. The requirements of our own research group and those of other members of the Observatory have been reviewed and discussed in a number of meetings with the result that we have prepared a set of comprehensive specifications describing a suitable instrument. These specifications were circulated among eligible microphotometer vendors. We expect to place an order for an advanced microphotometer during the next six months.

C. ATOMIC SPECTROSCOPY

The work on the absorption spectrum of aluminum has been extended by Parkinson and Reeves. The work emphasizes the important autoionized doublet of Al at 1936 Å and the ionization continuum. The recent experiments have been made with a volatile of aluminum, $Al(CH_3)_3$, which is mixed with the argon carrier gas. With this technique it is assumed that at the high temperature of the reflected shock, all the aluminum atoms of the volatile are released and available for the absorption process. This assumption allows the quantity of absorbing atoms to be computed and absolute oscillator strengths or cross sections evaluated. Unlike the earlier work of Garton, Parkinson and Reeves (1964) with powdered solids, the final f-value does not depend on the oscillator strength of a reference line. A list of preliminary f-values and peak cross sections for the doublet at 1932 - 1936 Å as well as the continuum cross section at the series limit is given in Table I. The f-values of the lines from the volatile techniques are about twice as large as determined with the powdered solid techniques. The reason for this difference has not yet been determined.

The values of the cross sections for absorption of the aluminum ionization continuum is vital in determining whether Al causes the drop in the solar continuum near 2085 Å. As part of her Ph.D. research program, Mrs. A. Dupree is carrying out the evaluation by reversing the usual approach to abundance determination. The value of the continuous absorption coefficient (K_λ) per gram of solar material is determined on either side of the drop in the solar spectrum. This is done by selecting two lines of the same element, with known oscillator strengths, photospheric abundance, and measured equivalent width in the sun. With the proper Milne-Eddington curve of growth, the absorption coefficient is evaluated. The solar abundance of Al and the measured cross section can then be used to determine if the photoionization of aluminum can make up for the abrupt decrease in continuum intensity.

The research on the aluminum spectrum has stimulated our interest in other similar atoms, in particular spectra which exhibit marked autoionization series and strong Fano type profiles. Thallium and barium are excellent, known examples of this, and research has started in collaboration with Professor W.R.S. Garton. The first observations recorded photoelectrically the course of continuous and line absorptions beyond the series limit of thallium and barium by heating these metals in an electric furnace. The line shape parameters for this autoionizing series will be evaluated and compared to the similar work in the shock tube at much higher temperature.

The experiments for the simultaneous shock tube measurement of relative iron and chromium f-values and the ratio of f-values have been actively pursued by Drs. Tobey and Huber. Iron and chromium atoms were introduced into the test section of the shock tube as carbonyls premixed with argon. Shock temperatures of 5000-6000° enabled the population of high atomic levels, while at the same time the concentration of iron and chromium was minimized and an excessive spread of strong resonance lines prevented. At these relatively high temperatures, it was necessary to use a spectrographic shutter at the slit to prevent excessive emission from exposing the photographic plate. A high speed shutter was used with a closure time of approximately 50 microseconds. The plates were obtained with the 3 meter vacuum spectrograph and were scanned on a Joyce Loebl microdensitometer. The experimental equivalent widths were then determined from the scans.

The total number density of absorbing atoms was calculated from the experimentally determined temperature and density through the EXCIT 3 computer program. This program includes solutions to the Saha-Boltzmann equation for several simultaneously present gases. While the plates contain a great number of absorption lines from which f-values can be determined, the main aim of the experiment was to select iron-chromium pairs which have, in the sun, nearly the same equivalent width and occur in the revised Rowland catalogue as unblended lines in the solar spectrum. With the further condition of a wavelength region restricted to 3000-4000 Å, 9 suitable lines were used to provide 6 iron-chromium pairs. The results of this experiment were used for a determination of relative solar abundance of iron and chromium. The uncertainties both in the experimental f-value ratios and in the solar equivalent widths indicate that a larger number of line pairs will be required. In addition, the solar continuum is extremely uncertain in this wavelength region, and we must make laboratory determinations at longer wavelengths than 4000 Å. Preliminary results of this experiment are listed in Table II.

Work on this technique will continue at longer wavelengths and with other volatile metal compounds.

Mr. Gerald Newsom has continued the measurements of the oscillator strengths of the autoionized calcium lines near 6350 Å. Since these calcium lines were required in absorption, but at a high shock temperature, a correction was necessary in the computer program to calculate the contribution to the observed line self emission from the shock. This effect has only recently been considered, and gf-values are not yet available.

The continuing problem of the emission reversals near the center of strong absorption lines in the shock tube spectra has been investigated further. The possibility that the coaxial flash tube might heat up the shock significantly during the discharge has been checked. If such heating were significant, the absorption would take place while the shock was anomalously hot and thus give a broader line than the cooler emission from the shock. Inserting an interference filter between the flash and shock removed nearly all such heating, yet the reversals remained, disproving this idea as the sole cause of the reversals. The second suggestion depended on the fact that the spectroscopic sample is loaded as a powder near the center of the shock tube. The vaporization excitation and ionization of this powder may form a significant heat sink in the center of the shock tube, yielding a cooler center and hotter outer regions in the reflected shock. Near line center, where the absorption coefficient is highest, the hotter outer regions give a strong emission, while in the wings of the lines, emsssion appropriate to a mean temperature through the tube is given. Hence the emission as one moves away from line center mirrors the temperature profile as one moves in from the boundary of the shock tube. To check this theory, the powdered sample was added near the shock tube wall on the side towards the spectrograph. However, the emission reversals remained. Investigations on this exciting problem are continuing.

The high-speed spectral scans of the solar spectrum between 3900 Å and 8000 Å taken with the McMath

Solar Telescope at Kitt Peak National Observatory have been further reduced by Newsom in a search for more broad depressions in the continuum. A considerable number of depressions have been found, and a catalog is being prepared of all such features which show up on every scan of each wavelength region. When that is completed, possible molecular absorption will be investigated and those depressions which do not correlate with molecular bands will be compared with atomic absorptions observed in the shock tube and in stellar spectra.

The work of Dr. Weeks of our laboratory on the iron spectrum has continued. At present, the 300 spectral lines in the region 1998-1670, that are common to both shock tube and the furnace spectra, have been analyzed to give 21 new energy levels. Combinations between these new levels and lower known levels have produced lines which have been observed but are unidentified in the solar spectrum.

As part of her Ph.D. program, Mrs. B. Adams has been concerned with autoionization in calcium and magnesium atoms. Since mid-May investigations have been started pertaining to the possible application of Dr. P.G. Burke's close-coupling theories to these atoms. Hitherto, the theories have been applied only to hydrogen, helium and beryllium. Considerable modifications and extensions will be necessary. In particular, some method must be found to allow for the core distortion of the ionized atoms upon bombardment with the electrons. If successful, these calculations will provide accurate predictions of resonant absorptions and thus, also predict doubly-excited states. Dr. B. Shore, who recently joined our research group, has also undertaken theoretical study of the doubly-excited states of calcium-like atoms.

Possible mechanisms are under study to explain the observed discrepancy in chemical abundances between the solar corona and the photosphere. The Boltzmann equation with a binary collision integral has been used to determine diffusion velocities in the coronal plasma. In particular, the effects of diffusion caused by a temperature gradient, so-called "thermal diffusion", are being investigated. Steady state solutions for a two-component plasma are evaluated using published chromosphere-corona models. Thermal diffusion creates greatly enhanced ion concentrations in the hotter temperature regions of the corona. The time scale for this phenomenon is less than the characteristic lifetime of coronal condensations. This work is being carried out by Mrs. A. Dupree as part of her Ph.D. program.

A number of new computer programs have been written which permit rapid reduction and analysis of the experimental shock tube data and photographic plates. All of our programs are consistent with the presentation of microphotometer scans on punched cards. In a two pass program, the computer determines the optical depth as a function of wavelength for the absorption spectrum. A new program has now been prepared which takes the reduced microphotometer data on punched cards and uses the method of least squares to unfold overlapping line profiles. At present, Gaussian or Lorentzian line profiles may be used with account being taken of a slowly varying continuous background absorption. The program includes the integral of the absorption coefficient over frequency and thus a rapid determination of relative oscillator strengths is possible. By including several lines of known absolute gf-values in the reduction, the oscillator strengths of previously unmeasured lines can be found.

Calculations of atomic and molecular partition functions are being written for an IBM 7094 computer. Atomic energy levels have been obtained from the National Bureau of Standards on magnetic tape to speed the data handling. Simultaneous solution of the Saha equation with both atomic and molecular species present is being programmed to give accurate knowledge of the absolute populations of the various states in both atoms and molecules.

D. MOLECULAR SPECTROSCOPY

Early in this year we undertook the study of the laboratory absorption spectrum of shock heated carbon monoxide in the spectral region below 2000 Å. The results of this experiment led to the identification of the Fourth Positive System of carbon monoxide in the ultraviolet spectrum of the sun. The details of this work have been published in the Astrophysical Journal as "Carbon Monoxide in the Ultraviolet Solar Spectrum";

a copy of this paper is attached. Briefly, the appearance and form of the shock tube spectrum of CO appears to account for a number of the observed features in the rocket ultraviolet solar spectrum. In the case of the solar spectrum, the Fraunhofer lines disappear and limb brightening begins at the wavelength of 1550 Å. This corresponds to the position of the (0,0) band of the Fourth Positive System of CO. A large number of features in the solar spectrum to the red of 1550 Å have been correlated with vibrational and rotational structure in the CO molecule. The identification has stimulated work into the quantitative measurement of the absorption properties of carbon monoxide in the wavelength range $\lambda\lambda$1500-2000. The object of this research is to experimentally measure the absorption coefficient of carbon monoxide as a function of wavelength over a range of temperature in the vicinity of 5000°K. These results will then be applied to theoretical calculations of the outer layers of the sun in the vicinity of the temperature minimum.

To date, a number of calibrated spectrographic plates of carbon monoxide have been obtained with the 1 meter vacuum spectrograph (8 Å/mm). These spectra are of the carbon monoxide in absorption. The CO gas is raised to the appropriate temperature (near 5000°K) using standard reflected shock techniques. Plates have been obtained using both narrow (about 0.2 Å) and wide (about 2 Å) slits. All of these plates are in the process of reduction. Because of resolution problems, work has proceeded to the 3 meter vacuum spectrograph (2.8 Å/mm) in order to identify and at least partially resolve the rotational structure of the various vibrational bands. Reasonably good spectrographic plates of carbon monoxide in absorption at temperatures near 5000°K have been obtained, accompanied by microwave discharge emission spectra of the CO. An extensive identification program is underway.

Future work calls for several calibrated spectra using the 3 meter instrument. Additional plates will be taken as necessary. Final results will yield absorption coefficients for broad features of the spectrum in conjunction with f-numbers for the unresolved features of the spectrum.

TABLE I. SUMMARY OF RESULTS

λ_o	1932 Å	1936 Å
$\Delta\lambda$	1.44 ± 0.01 Å	1.39 ± 0.03 Å
$f_{present}$	(0.103 ± 0.008)	(0.087 ± 0.008)
$f_{Al:Ca}$	(0.049 ± 0.002)	(0.033 ± 0.002)
f_{Froese}	0.08	0.08
σ_{max}	$(116\pm15)\times10^{-18}\,cm^2$	$(146\pm8)\times10^{-18}\,cm^2$
$\sigma_{cont.\ 1936}$	$5.9\times10^{-18}\,cm^2$	
$\sigma_{cont.\ 2085}$	$8.2\times10^{-18}\,cm^2$	

TABLE II

Lines	gf_{Cr}/gf_{Fe}	gf_{Cr}/gf_{Fe} (lit.)	relative gf meas. / relative gf lit.
Cr 3639.804 / Fe 3268.243	81	36	2.25
Cr 3639.804 / Fe 3595.308	40	22	1.82
Cr 3436.196 / Fe 3549.872	261	121	2.15
Cr 3436.196 / Fe 3322.481	11.8	5	2.36
Cr 3768.733 / Fe 3325.479	4.7	4.0	1.18
Cr 3768.733 / Fe 3207.081	5.3	4.5	1.18
Cr 3238.088 / Fe 3462.358	19	---	---
Cr 3238.088 / Fe 3628.098	17	---	---